MASSIVE PARALLEL PROCESSING FOR LOW COST A-SI PRODUCTION

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ABSTRACT: A large batch approach to the manufacturing of amorphous silicon photovoltaic modules is described. A cost analysis shows the cost of production to lie in the range \$1-2/W_p depending largely on the labor content. The consistency and reproducibility of this approach is illustrated with statistical production data. The longevity of the module is demonstrated by long-term exposure data. Recent improvements in module performance are documented. The influence of spectral variation on the energy delivery of tandem junction modules is quantified.
Keywords: a-Si, Module Manufacturing, Cost Reduction, Performance

1 INTRODUCTION

PV module production based on thin films has been initiated by several groups and promises to capture a significant market share for many PV segments. However, truly cost-competitive and large-scale production has not, in general, been realized, making it clear that the manufacturing approach is critical. This paper analyzes the attributes of a particular approach to low cost, high throughput production of amorphous silicon modules. The approach involves massive parallel processing of multiple substrates in a single, compact vacuum chamber in which a-Si deposition is conducted by PECVD. This technology, as part of an *Integrated Manufacturing System (IMS)*, has been installed by EPV for a-Si production in our pilot line in Princeton, for DunaSolar in Budapest, and for CalSolar in Sacramento, with further contracts currently being executed. These facilities manufacture a $0.79m^2$ dual-junction a-Si module rated at 40 watts (stabilized) under standard reporting conditions. This article will illustrate the performance of the *IMS* for a-Si through analysis of manufacturing cost, and presentation of statistical production data and module performance.

2 MANUFACTURING APPROACH

2.1 Technology choice

The specific advantages and disadvantages of thin-film and wafer-based photovoltaic modules have been discussed at length [1]. Thin-film technologies enjoy the substantial advantages of reduced parts handling (resulting from the use of large substrates and monolithic integration), and of low cell material requirements (only $7g/m^2$ for a-Si). These major advantages can result in a low module manufacturing cost, expressed in \$/W_p, even at the lower conversion efficiencies usually exhibited by thin films. In addition, thin films are advantageous in terms of energy payback time (e.g. 1.8 years for CIGS versus 3.3 years for c-Si [2]). This issue is important if PV is to be deployed as a renewable energy source.

In order to realize the advantages of thin films, the manufacturing plant and process must perform well in terms of yield, consistency, reproducibility, throughput, and up-time, with low capital cost and low direct and indirect materials costs.

The three main industrial approaches to a-Si manufacturing are large batch, in-line multi-chamber, and roll-to-roll. Cluster tool processing is also under consideration. For reasons of low capital cost, high up-time and excellent process control, EPV chose to develop a large batch process. Continuous engineering improvements have resulted in the mature process that is utilized in EPV's $5MW_p$/y *Integrated Manufacturing System*.

2.2 Process overview

Within the a-Si deposition chamber, deposition is performed by PECVD on 48 substrates simultaneously using multiple RF electrodes powered at 13.56MHz. The substrates are stationary, and oriented vertically. The manufacturing facility is furnished with two such independent a-Si deposition chambers, each capable of a throughput of $2.5MW_p$/y.

A condensed flow chart of the major process steps used to produce the standard glass-glass EPV-40 module is shown in Figure 1 below. The metallization is performed by in-line magnetron sputtering. All three patterning steps are performed by laser ablation. The encapsulation step encompasses seven distinct operations, including edge isolation, foil bonding, EVA application and lamination, attachment of wires, potting, and mounting rail attachment. The I-V testing is performed using a flash simulator.

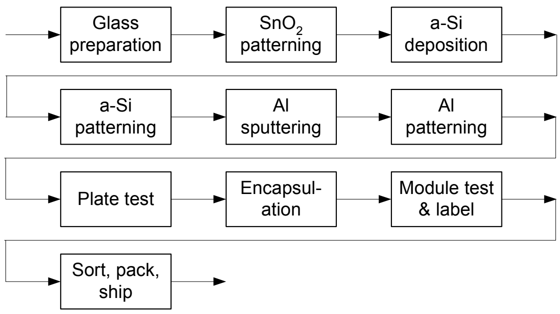

Figure 1: Major process steps for a-Si manufacturing

3 MANUFACTURING COST

Based on actual operating experience, we have calculated the manufacturing cost for frameless, tandem junction a-Si modules produced in a $5MW_p$/y facility using EPV's massive parallel processing approach without use of automation. For these calculations, the average stabilized module power was assumed to be 40W. The itemized costs are shown in Table I below. The direct and indirect materials costs are known accurately via factory purchases. The US labor costs are based on competitive salaries. Direct labor comprises 16 different areas for manufacturing and shipping, while indirect labor comprises supervisors, QC, maintenance, and engineering. The table includes a 15% allowance for SG&A (marketing and sales, purchasing, controller, General Manager and assistant). For the USA, the maunufacturing cost is calculated to be $1.79/W_p$, while for Eastern Europe, for example, the cost is $1.24/W_p$. Lower costs are achievable through process improvements leading to increased module efficiency, increased yield, or decreased cycle time. In addition, some reduction in materials cost should be possible via bulk purchasing. It goes without saying that quality of the work force may exert either a positive or negative influence on manufacturing cost, while partial automation could significantly reduce labor costs in those regions of the world where labor costs are high.

Table I: Manufacturing costs ($/W) for 40W, frameless, tandem junction a-Si modules produced using (non-automated) large-batch processing

Category	USA	Eastern Europe
Direct materials	0.71	
Indirect materials	0.14	
Yield loss (10%)	0.08	
Utilities	0.05	
Replacement parts	0.02	
Total materials	**1.00**	**0.95**
Direct labor (with benefits)	0.47	
Indirect labor (incl. mainten.)	0.22	
SG&A (15%)	0.10	
Total labor	**0.79**	**0.29**
Total cost	***1.79***	***1.24***

4 PRODUCTION DATA

4.1 Performance statistics

As an example of the high yield and consistency obtainable using large batch processing, we show in Fig. 2 a frequency histogram for the initial wattage produced by all modules manufactured in five consecutive a-Si depositions. The runs were conducted within the first six months of production from a new facility.

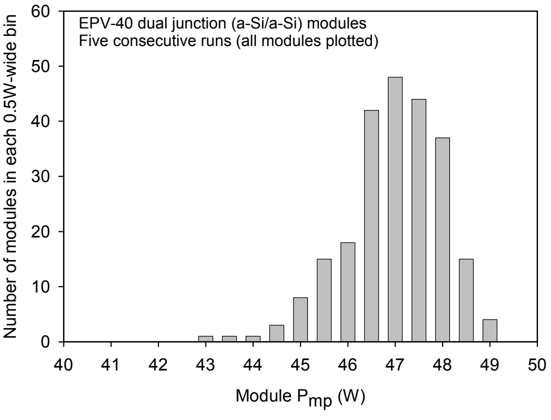

Figure 2: Initial wattage distribution for 5 consecutive depositions, representing 11.1kW of production.

In each run, 48 plates are coated, totaling 240 plates over the five runs. Three plates were removed for diagnostic purposes and were not processed into modules. For the 237 resulting modules, the average initial module power P_{mp} was 47.0W, the standard deviation was 1.0W, and the aggregate power was 11.1kW. (The modules were deposited on commercially available TCO-coated glass, and did not incorporate a ZnO back reflector.) The average volume of product produced per deposition cycle per chamber is thus 2.2kW initial, or 1.9kW rated. These statistics demonstrate high yield, good intra-run consistency, and good inter-run repeatability.

4.2 Deposition uniformity

Thickness variation of the amorphous silicon is believed to be a more serious problem for production of tandem devices rather than for single junction devices. For example, it could result in current mismatch between junctions of non-optimal thickness, or top-junction shunting effects. Various steps have been taken to achieve uniform deposition of the amorphous silicon over the entire substrate. Figure 3 shows a spatial mapping of the total a-Si thickness (measured by stylus profilometry) for a p-i-n/p-i-n device (plate 128-21) deposited on a standard 63.5 cm x 124.5 cm TCO-glass substrate. In general, the thickness uniformity is very good (average thickness 537nm, standard deviation 13nm), with only a couple of edge issues remaining to be addressed.

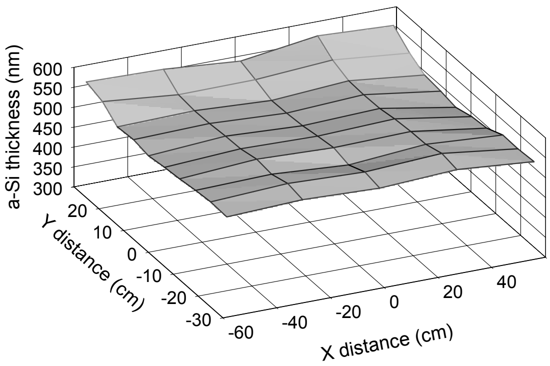

Figure 3: Spatial mapping of the total a-Si thickness over a 63.5 cm x 124.5 cm substrate.

The resulting uniform and attractive appearance of the module makes it highly desirable for BIPV applications.

5 MODULE PERFORMANCE

5.1 Earlier modules: life testing

The long term performance of thin film a-Si is of the utmost interest. Earlier versions of the EPV-40 have been monitored by Sandia National Laboratories for over four years. In this program, modules are exposed continuously outdoors and are moved from the exposure rack to a 2-axis solar tracker for periodic performance testing. The solid points in Figure 4 shows the P_{mp}(SRC) derived by Sandia from measurements on EPV module E257-18, exposed under open-circuit conditions. Standard Reporting Conditions (SRC) are defined as 1000 W/m^2, AM1.5, cell temperature 25°C.

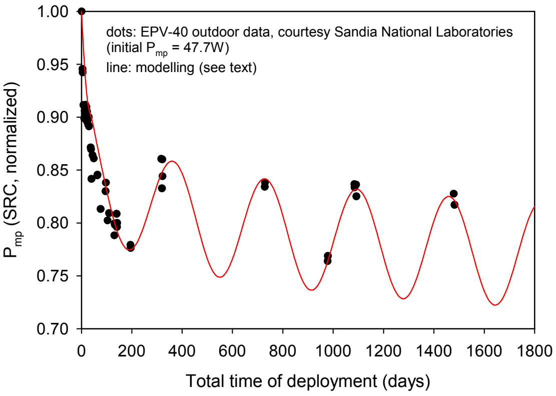

Figure 4: Outdoor data (and curve fit) for the EPV-40 over a 4 year period.

The solid line is a fit to the data using an expression for the efficiency that depends essentially logarithmically on time, with an additive seasonal factor that is approximated by a sinusoid. The latter factor reflects the temperature dependences of the degradation and annealing processes. This type of expression has been used by Muirhead et al. [3]. The exact expression used was

$$P(t) = a - b*\sin(2\pi(t+c)/365.25) - d*\ln(t+e) \qquad (1)$$

where P(t) is the normalized power at time t (days), a = 0.95, b = 0.05, c = -90, d = 0.024, e = 1. The module was deployed on 8/27/98. The value of the phase factor c implies that the peak efficiency is reached around the end of the summer. With b = 0, the seasonally-averaged power can be extrapolated to 10 and 20 years as shown in Table II. It will be interesting to see if this holds.

Table II: Average module power according to eqn. (1)

Year:	0	1	4	10	20
Normalized power:	1.0	0.81	0.77	0.75	0.74

5.2 Newer modules: improved stability

A vigorous program was instituted at the beginning of 2002 at EPV to improve the stabilized efficiency of a-Si modules. To support this effort, a fully-automated accelerated light soaking (ALS) station was built in order to enable rapid ranking of a-Si cells produced using a variety of a-Si deposition recipes. Small area test cells are generated by cutting samples from standard 0.79m^2 plates and defined by chemical etching of the Al. The ALS station alternates between soaking at an irradiance of 47 suns (for pre-determined time intervals) and I-V measurement at 1 sun. From the temperature dependence of V_{oc}, the temperature of the a-Si during soaking was estimated to be 95°C.

Figure 5 shows the dependence of 1 sun cell efficiency on accumulated light soak time for tandem cells produced using EPV's old standard recipe and cells using a new recipe that embodies several key concepts. (The starting efficiencies have been arbitrarily placed at t = 0.1s on the log time axis.) Despite having a lower initial efficiency, the new cells exhibit reduced degradation, so that after ALS soak times equivalent to over 100 hours of 1 sun soaking, their efficiency is greater than that of the old standard cells.

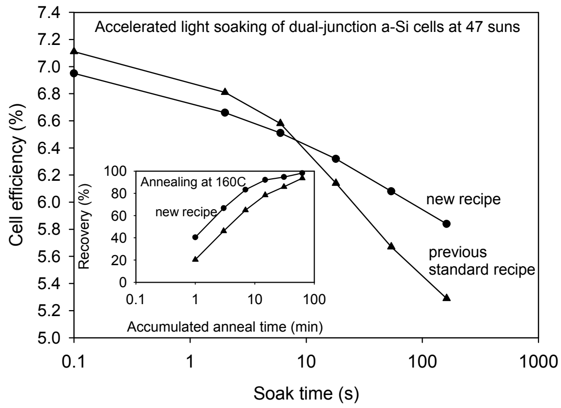

Figure 5: High intensity light soaking of tandem junction cells produced using two different recipes for a-Si deposition.

The graph inset in Figure 5 shows the rate at which these two types of cell anneal. The annealing was performed at 160°C, and the y-axis parameter is defined as

$$\text{Recovery} = (\eta(t) - \eta_{ls})/(\eta_i - \eta_{ls}) \qquad (2)$$

where $\eta(t)$ is the cell efficiency after annealing for time t, η_{ls} is the cell efficiency after light soaking, and η_i is the cell efficiency before light soaking. It is interesting to note that the cell with the higher annealing rate (new recipe) suffered the smaller efficiency loss upon light soaking.

Modules produced using this new class of recipe gratifyingly appear to have a higher stabilized power. Table III shows the P_{mp}(SRC) of such a module as a function of outdoor deployment time.

Table III: Measured module power (W) as a function of deployment time for new recipe

Days	0	7	30	49	84	136
Power	45.6	42.8	41.6	41.4	41.1	41.3

Figure 6 shows the I-V curve of this module taken after it had been exposed outdoors for 136 days. The measured P_{mp} of 41.3W represents a power loss of 9.4% relative to its initial power.

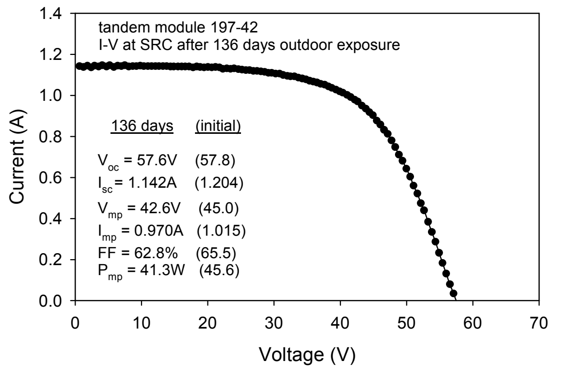

Figure 6: I-V curve for an EPV-40 module produced using a new a-Si recipe taken after 136 days of outdoor exposure.

5.3 Energy delivery and spectral effects

While EPV's standard module employs tandem junction devices, a comparison of their performance with modules employing single junction devices is of interest, since manufacturing costs would be slightly lower for the latter type of module. Tandem junctions exhibit reduced power loss on light soaking, and are therefore advantageous from this point of view, but might be expected to pay a small penalty in overall energy delivery because of junction mismatch under different spectral conditions. King et al. have explored related effects [4], and energy delivery calculations have been previously presented in ref. [5]. At EPV, studies of energy delivery as a function of module type have been conducted using a Campbell Scientific CR10X datalogger and a LI200X cosine-corrected pyranometer.

Figure 7 shows representative data collected in one study conducted in early September, 2002. In this study, single and tandem junction a-Si modules (previously exposed for 85 days and 133 days) were mounted at an angle of 45°, facing 30° west of south, and connected to constant voltage loads. The loads were based on a shunt-regulating Darlington power transistor. The voltage was set equal to the maximum power voltage of the module as previously determined under SRC conditions.

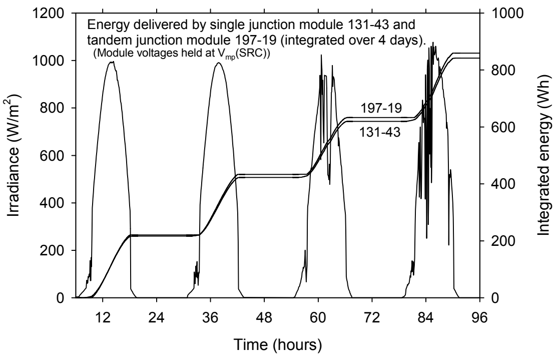

Figure 7: Irradiance and integrated energy for single junction and tandem junction modules (held at $V = V_{mp}$(SRC)) over a four day period.

Table IV summarizes the numerical results of this study. The integrated energy delivered by the tandem module (averaged over the four day period) was 214.8 Wh/day, compared to 210.4 Wh/day for the single junction module.

Table IV: Measured energy delivery of single junction and tandem junction modules held at $V = V_{mp}$(SRC).

Module	E_{int} (Wh/day)	P_{1000} (W)	E_{norm} (E_{int}/P_{1000})
131-43	210.4	35.4	5.94
197-19	214.8	36.6	5.87

At the elevated operating temperature of the modules, and hence at non-optimal load voltages, the powers delivered by the modules at 1000W/m^2 were 36.6W and 35.4W, respectively. Normalized by these figures, the integrated energy figures become 5.87 and 5.94, respectively. These figures serve to quantify the effect of spectral mismatch. For these particular modules, under the load condition chosen, and for the particular four-day period, the integrated energy delivered by the tandem was reduced by 1.3% relative to what would be expected in the absence of spectral effects. (It was confirmed that this loss could not be attributed to intensity effects; relative to their performance at an irradiance of one sun, at 0.1 sun irradiance with identical spectral content, single junction cells lost 9.9% of their efficiency, while tandem cells lost 7.2%.) A more complete analysis of such factors will be undertaken in the future using a maximum-power-tracking load. It is hoped that conclusions can be drawn regarding energy delivery for tandem junction modules possessing different magnitudes and sign of junction mismatch for different seasons.

6 CONCLUSIONS

Massive parallel processing is shown to be an attractive and powerful method of manufacturing thin film a-Si PV modules. In the US, the manufacturing cost is less than \$2.00/W_p, while in low labor cost regions of the world \$1.25/W_p can be achieved. Over five consecutive depositions, the average tandem junction module power was 47W with a standard deviation of 1W, with all modules functional and exceeding 43W. These figures attest to the high yield and reproducibility of the process, a factor that is crucial in achieving a low manufacturing cost. The fundamental longevity of the module has been independently verified by four years of testing by Sandia National Laboratories. Newer a-Si recipes have been devised that exhibit reduced power loss upon light soaking and higher stabilized efficiencies. The effect of current mismatch due to spectral variations was shown only to have a small impact on integrated energy delivery by tandem junction devices. Further advances in this type of technology are possible, through incremental optimization, improvement of light trapping, and introduction of microcrystalline silicon.

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